

Uncovering the Seasonality of Storm-Driven Southern Ocean Heat and Carbon Uptake

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ABSTRACT: The Southern Ocean is an important region for both heat and carbon uptake, due in large part to wind-driven circulation. This region also continually experiences strong winds associated with the passage of synoptic storms, which influence the upper ocean through strong fluxes of momentum, heat, freshwater, and gases. While studies have found that storms can induce strong carbon outgassing, their role in the combined uptake of heat and carbon remains unknown. In this work, we explore the climatological impact of storms on the Southern Ocean combined heat and carbon uptake through two preindustrial coupled climate model runs with contrasting seasonal carbon fluxes. We use a feature tracking system to identify storms and create composites for storm-following and poststorm anomalous fluxes of heat and carbon. Storms induce a net anomalous release of heat and carbon from the ocean throughout the year, with clear seasonality in the magnitude of the fluxes that coincide with the background seasonal cycles. We find a strong model dependency for the storm-driven anomalous carbon fluxes, in terms of both the seasonal range and timing of maximum outgassing. Storm-induced anomalous fluxes are dampened on the order of days after the storm passes, with a small continued release of heat that is most persistent in the winter. Our study underlines the high uncertainty about the seasonal nature of storm impacts on the ocean and suggests that evolving atmospheric and oceanic conditions could impose opposing shifts in the future seasonality of storm impacts.

SIGNIFICANCE STATEMENT: Strong winds within storms can enhance heat and carbon exchange between the atmosphere and ocean, which plays an important role in setting Earth's climate. In this study, we identify storms in two climate models to isolate their impacts on heat and carbon exchange in the Southern Ocean. We find that Southern Ocean storms release both heat and carbon into the atmosphere. The magnitude of this release varies across seasons, with summer storms releasing most heat and summer and autumn storms releasing more carbon. Our work shows the importance of seasonal timing for storm activity, which can have important implications for heat and carbon cycling as the atmosphere and ocean continue to evolve within our warming climate.

KEYWORDS: Southern Ocean; Extratropical cyclones; Surface fluxes; Coupled models

1. Introduction

The prevailing westerly winds over the Southern Ocean spanning from ~40°S to the Antarctic continent are responsible for the large-scale overturning in the Southern Ocean and bring up old, cold, and carbon-rich circumpolar deep water to the surface (Toggweiler and Samuels 1993; Russell et al. 2006; Marshall and Speer 2012). This upwelling results in the recycling of natural carbon in the Southern Ocean (Gruber et al. 2019) and the uptake of over 75% of anthropogenic heat (Frölicher et al. 2015; Williams et al. 2024) and around 40% of anthropogenic carbon (DeVries 2014; Gruber et al. 2019). The disproportionate uptake of carbon and heat provides a first-order control on the global climate response to emissions (Williams et al. 2023).

In addition to these prevailing westerlies, the Southern Ocean also experiences a continual passage of extratropical storms through the midlatitude storm track. As the Southern Ocean has very little land within the storm track, these low pressure systems can proceed unabated across large swaths of the Southern Ocean and induce strong anomalous fluxes of heat, mass, and momentum between the ocean and atmosphere. While the mean overturning of the Southern Ocean is driven mainly by the prevailing westerlies, there is a strong storm-driven component in the atmosphere that can also contribute to air-sea fluxes, in both a time-varying and long-term-mean sense. The continual presence of midlatitude storm systems drives intraseasonal variability in CO₂ fluxes that can obfuscate the seasonal cycle and annual-mean behavior (Monteiro et al. 2015), and synoptic activity generates deeper mean mixed layers and stronger seasonal cycles in the high-latitude Southern Hemisphere (Whitt et al. 2019).

As a climatological feature, the Southern Hemisphere storm track exhibits important seasonality that can impact the air-sea fluxes from individual storms. From summer to winter, the storm track transitions from an annular pattern to a more poleward-intensified, spiraling structure (Hoskins and Hodges 2005; Priestley et al. 2020). Through this seasonal transition, storm activity shifts across different dynamical and biogeochemical ocean regimes, changing the background mean oceanic component of

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the atmosphere–ocean gradients that drive fluxes of heat and carbon. At the same time, the Southern Ocean experiences strong seasonal cycles in both its heat and carbon uptake, driven by a combination of insolation, circulation, and biological activity. The seasonal cycle for CO₂ fluxes, in particular, remains highly uncertain, with existing models and data products exhibiting a wide variety of magnitudes and phases on seasonal time scales (Hauck et al. 2023). Thus, to understand the climatological impact of storms in the Southern Ocean, it is important to understand the seasonal variability in storm-induced anomalies and how they may relate to the background seasonal cycles.

Observing storm-induced high-frequency variability in Southern Ocean heat and carbon uptake is challenging as hazardous winds and wave conditions often prevent shipboard sampling. Nevertheless, there is a growing body of literature on the impact of storms on the Southern Ocean carbon fluxes using models and autonomous observations. Glider studies have found local CO₂ outgassing and pCO₂ feedbacks during summertime storms, defined as periods of sustained winds, and have attributed these changes to storm-induced vertical entrainment (Nicholson et al. 2022; Toolsee et al. 2024). Composites of Biogeochemical Argo (BGC-Argo) profiles have also shown large-scale storm-driven outgassing throughout the Southern Ocean and have found a role of atmospheric surface pressure changes associated with storms in driving this outgassing (Carranza et al. 2024). Observational setups continue to face difficulties resolving the full spatial and temporal scale of storm forcing: Gliders produce high-resolution measurements within a small area, and the 10-day resampling period of BGC-Argo floats means that many storms remain unsampled or sparsely sampled.

Because of the difficulties with observations, numerical modeling studies provide a complementary viewpoint to storm impacts on the ocean. Fully coupled models can provide an internally consistent view of the atmosphere–ocean system during synoptic activities, provided that they can adequately represent the properties of midlatitude storms. However, there is significant disagreement among models in their representation of storm activity and their associated heat and carbon fluxes in the Southern Ocean. When extratropical storms are tracked through lower- and midtropospheric vorticity fields, Coupled Model Intercomparison Project phase 6 (CMIP6) models show improved storm representation, although there is a persistent low bias in Southern Hemisphere storm genesis and an equatorward bias in the storm-track density, particularly in winter (Priestley et al. 2020). A complementary ocean-only model study in Carranza et al. (2024) also found storm-driven CO₂ outgassing, although the modeled outgassing was an order of magnitude smaller than that in the BGC-Argo floats. As of yet, however, there has not been a study of the oceanic response to storms in a fully coupled model, which is necessary for understanding heat fluxes associated with storms and the relationships between storm-associated oceanic changes, background ocean temperatures and circulation, and midlatitude storm tracks (Woollings et al. 2010, 2012).

This manuscript explores the climatology of storm activity over the Southern Ocean and the climatological impact of storms

on ocean heat and carbon uptake using two state-of-the-art fully coupled climate models and storm-centered composites of anomalous fluxes. We consider the combined heat and carbon response to storms as, under periods of emissions, the relationship between changing ocean heat and carbon plays an important role in Earth's climate response (Williams et al. 2016). The use of a preindustrial run eliminates the need to separate impacts due to warming from those due to the background climate state. Storm-track locations and densities are expected to change under future warming through both emissions forcings and climate feedbacks (Son et al. 2009; Shaw et al. 2016; Banerjee et al. 2020; Priestley and Catto 2022b; Gentile et al. 2023). The continued uptake of heat and carbon from present-day anthropogenic carbon emissions provides an additional forcing on the Southern Ocean system in terms of the background ocean heat content and carbon content. Thus, our model results can provide context for how current-day storm impacts may already be a function of warming and the background Southern Ocean state.

In particular, we aim to understand how anomalous heat and carbon fluxes induced by storms can vary throughout the year to create a seasonal climatology that serves as a basis for understanding future changes in the storm track and impacts on Southern Ocean heat and carbon uptake. We hypothesize that stronger winds and enhanced storm activity in the austral winter will lead to larger heat and carbon release from storm forcing. For heat fluxes, this hypothesized storm impact would enhance the existing seasonal cycle as winter is a period of basinwide heat release. For carbon fluxes, the relationship between storm fluxes and the seasonal cycle will be model-dependent, owing to continued discrepancies in how models resolve the seasonal cycle of CO₂ fluxes. We hypothesize that there will also be a longer persistence in storm-driven signals in the winter as a result of their larger magnitudes. For this study, we will employ two models with contrasting background seasonal CO₂ fluxes to test whether the background seasonality plays a role in setting storm-induced anomalous fluxes throughout the year or whether our atmospheric-driven hypotheses hold across model differences.

In the next section, we introduce the GFDL coupled models Coupled Model version 4 (CM4), and Earth System Model version 4.1 (ESM4), used in this study alongside the TempestExtremes feature tracker used to identify midlatitude storms and create storm-centered composites of atmosphere and ocean fields. Section 3 describes the modeled Southern Hemisphere storm tracks and average atmospheric characteristics and compares them to those in the fifth generation European Centre for Medium-Range Weather Forecasts atmospheric reanalysis (ERA5) during the satellite period. Section 4 presents the composite air–sea fluxes of heat and carbon beneath Southern Hemisphere storms, their seasonal variability, and the adjustment in air–sea fluxes after the passage of the storm. To conclude, in section 5, we provide a critical discussion of our results, with a focus on how they relate to seasonal variability and how climate change may impact this seasonality.

TABLE 1. Overview of some of the architectural differences between the GFDL CM4 and ESM4 coupled models.

Component		CM4	ESM4
Atmosphere	Vertical extent	100 hPa	1 hPa
	Vertical levels	33	49
	Stratospheric ozone	Prescribed	Interactive
Ocean	Horizontal resolution	1/4°	1/2°
	Mesoscale eddy parameterization	Unparameterized	MEKE
	Biogeochemical model	BLINGv2	COBALTv2

2. Methods

a. The GFDL global coupled models

In this work, we analyze the results of two fully coupled numerical climate models developed by NOAA-GFDL as part of the recent CMIP6 (Eyring et al. 2016). CM4 (Held et al. 2019) and ESM4 (Dunne et al. 2020a) are built on different configurations of the Atmospheric Model version 4 (AM4), (Zhao et al. 2018a,b) and Ocean Model version 4 (OM4) (Adcroft et al. 2019), and an outline of some of the differences between the models can be found in Table 1. For both models, sea ice is represented using the Sea Ice Simulator version 2 (SIS2.0) sea ice model (Stern et al. 2017), and terrestrial dynamics are included through the Land Model version 4 (LM4) (Shevliakova et al. 2024). The atmospheric model has a horizontal resolution of around 1° in both CM4 and ESM4. CM4 uses a low-top atmospheric model with 33 levels extending to 100 Pa and a simplified chemistry scheme (Zhao et al. 2018a,b), while ESM4 uses a high-top atmospheric model with 49 levels extending to 1 Pa, as well as interactive tropospheric and stratospheric chemistry (Horowitz et al. 2020).

The OM4 ocean model is a MOM6 configuration with 75 levels using hybrid pressure/isopycnal vertical coordinates. MOM6 contains an energetics-based boundary layer scheme for ocean mixing (Reichl and Hallberg 2018) and parameterized restratification from mixed layer eddies and baroclinic instabilities (Fox-Kemper et al. 2011) with a submesoscale frontal length of 500 m and a time scale of 30 days (Adcroft et al. 2019). The ocean configuration used in CM4 has a nominal 0.25° horizontal resolution and no mesoscale eddy parameterization. The ocean configuration used in ESM4 has a nominal 0.5° horizontal resolution and includes parameterizations for mesoscale eddies. Thermodynamic coupling between the atmosphere and ocean occurs every 30 min in CM4 and every hour in ESM4; biogeochemical tracers are exchanged in both models every 2 h.

The ocean biogeochemical model in CM4 is the simplified biogeochemical model Biogeochemistry with Light, Iron, Nutrients and Gas version 2 (BLINGv2) (Dunne et al. 2020b), which includes diagnostic tracers for dissolved inorganic carbon (DIC), oxygen, alkalinity, dissolved organic and inorganic phosphate, and dissolved iron. The ocean biogeochemical model in ESM4 is Carbon, Ocean Biogeochemistry and Lower Trophics version 2 (COBALTv2) (Stock et al. 2020), which includes 33 tracers including carbon, alkalinity, oxygen, nitrogen, phosphorus, iron, silica, and calcium carbonate, as well as three phytoplankton functional groups.

The models are initialized with present-day climatological temperature and salinity fields obtained from World Ocean Atlas 2013 (Locarnini et al. 2013; Zweng et al. 2013). The CM4 model was spun up for 150 years using preindustrial boundary conditions and radiative forcing obtained from the CMIP6 protocol before starting preindustrial simulations [preindustrial control (piControl)] (Eyring et al. 2016), while a longer 400-yr spinup for the biogeochemical tracers was needed for the ESM4 model. The CM4 integration includes 6-hourly atmospheric snapshots and daily surface and interior ocean mean fields for 95 years, while the ESM4 integration includes 6-hourly atmospheric snapshots and daily surface mean fields for 100 years. Both simulations were conducted on a new high-performance computing system and are therefore not bitwise identical to the versions published for CMIP; however, the runs have similar climates to the CMIP published runs and are representative of the longer piControl simulations.

To visualize the role of synoptic time scales in setting the variability of air–sea fluxes, we show the fraction of variance within the 2–8-day bandpass-filtered time series of heat and carbon fluxes within both models (Fig. 1). The fraction of variance in heat fluxes around the Southern Ocean ranges from around 0.10 near the Antarctic coast to 0.25 around the northern flank of the Antarctic Circumpolar Current (ACC) and the subtropical gyres. The models show a high level of consistency in the regions that experience the largest fraction of variance in the higher frequencies (area-averaged correlation of 0.98). In contrast, carbon fluxes show higher fractions of variance within the main ACC region, and the fraction of variance within synoptic time scales can reach over 0.30. The models disagree on the regions with this highest fraction of variance and are moderately positively correlated (area-average correlation of 0.51). Thus, there is a significant level of high-frequency variability, and understanding the impact of storms can provide insights into the contribution from coherent, large-scale, and short-lived atmospheric features.

b. TempestExtremes feature tracking and comparison with ERA5

For this study, we utilize a Lagrangian feature tracker for midlatitude cyclones. In comparison with Eulerian metrics such as atmospheric eddy kinetic energy, which are useful for understanding large-scale storm-track statistics, a Lagrangian tracker focuses on isolating the impacts of an individual event throughout its lifetime. Feature trackers have been widely used for atmospheric studies of storm dynamics and biases

Fraction of variance within 2–8 day bandpassed fluxes

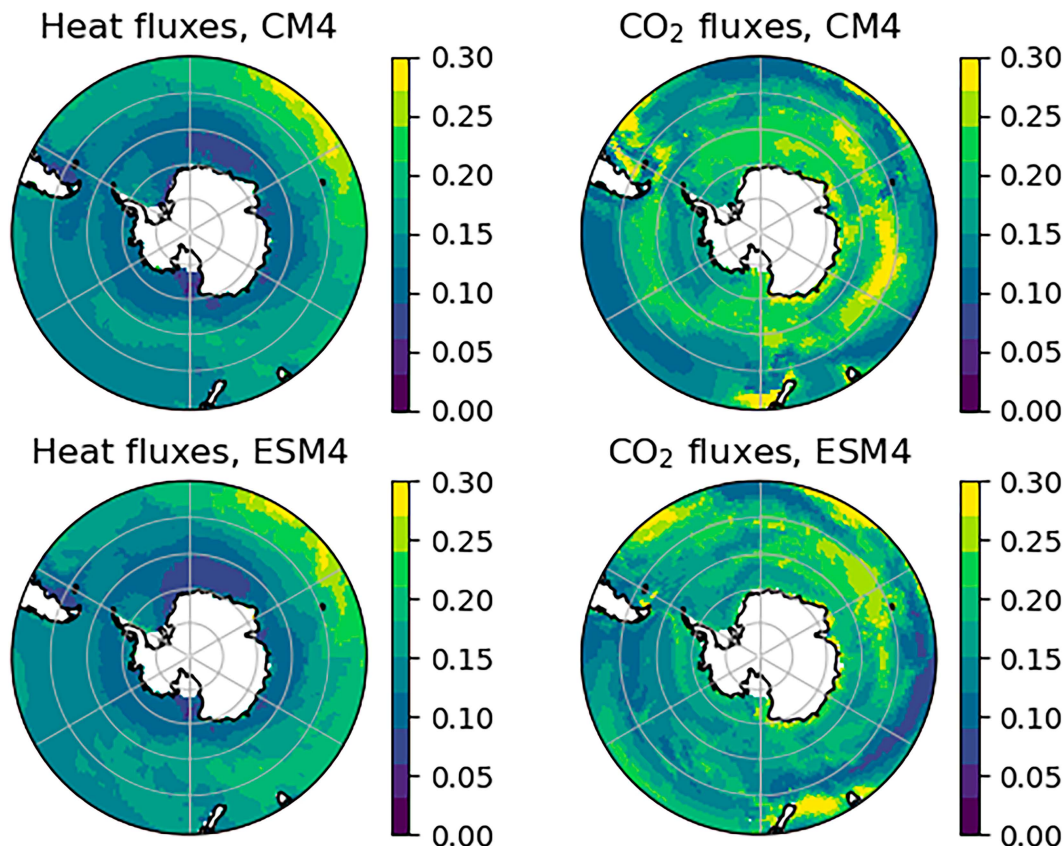


FIG. 1. Fraction of total variance in (top) CM4 and (bottom) ESM4 within periods of 2–8 days for (left) heat fluxes and (right) CO₂ fluxes. Values are calculated at each location as the ratio of variance within the 2–8-day bandpass-filtered fluxes over the detrended fluxes in the piControl simulations.

(Hoskins and Hodges 2002, 2019; Priestley and Catto 2022b,a). The criteria for identifying and tracking synoptic-scale storm events in the Southern Ocean are application dependent, and many different approaches exist in the literature (Neu et al. 2013).

To track storms in the Southern Ocean, we use the TempestExtremes v2.1 package (Ullrich et al. 2021). TempestExtremes is an efficient and variable-agnostic feature detector and tracker that can identify single-point and large-scale features. For this study, feature identification criteria were chosen to ensure a large sample size of transient storms for robust statistical analysis and to focus on the atmosphere–ocean interface, which should correspond with changes in air–sea fluxes. The baroclinic structure of extratropical cyclones can result in a horizontal displacement between aloft features like 850-hPa vorticity maxima and surface lows. Thus, we use a surface-based method to identify storms based on sea level pressure (SLP) similar to the extratropical storm-tracking methods used in Ullrich et al. (2021) and Carranza et al. (2024).

To detect storms, we use 6-hourly snapshots of SLP and identify local SLP minima between 30° and 90°S. Candidate

storm centers are required to have a closed contour of 2 hPa within a great circle radius of 6°, and centers within 8° of a deeper SLP low are removed to account for complex systems that can have multiple local SLP minima. Storm centers are then linked using a nearest-neighbor algorithm to form storm trajectories. To focus on long-lived and long-track storms, we considered only storm tracks longer than 60 h, allowing only a maximum temporal gap of 18 h between identified low pressure centers. In addition, storm tracks must cover a minimum distance of 12° from the initial location to remove stationary pressure minima associated with low zonal wavenumbers and longer periods of climate variability.

We use the same storm-tracking workflow to compare with surface atmospheric fields from the ERA5 (Hersbach et al. 2020) for the years 1979–2022. ERA5 is a global reanalysis with 31-km horizontal resolution that includes both in situ and satellite observations, with current-day reanalyses including more than 25 million data points each day. The period of 1979 onward coincides with the inclusion of satellite observations and better observational coverage of the Southern Ocean, which results in a higher degree of certainty for Southern Hemisphere

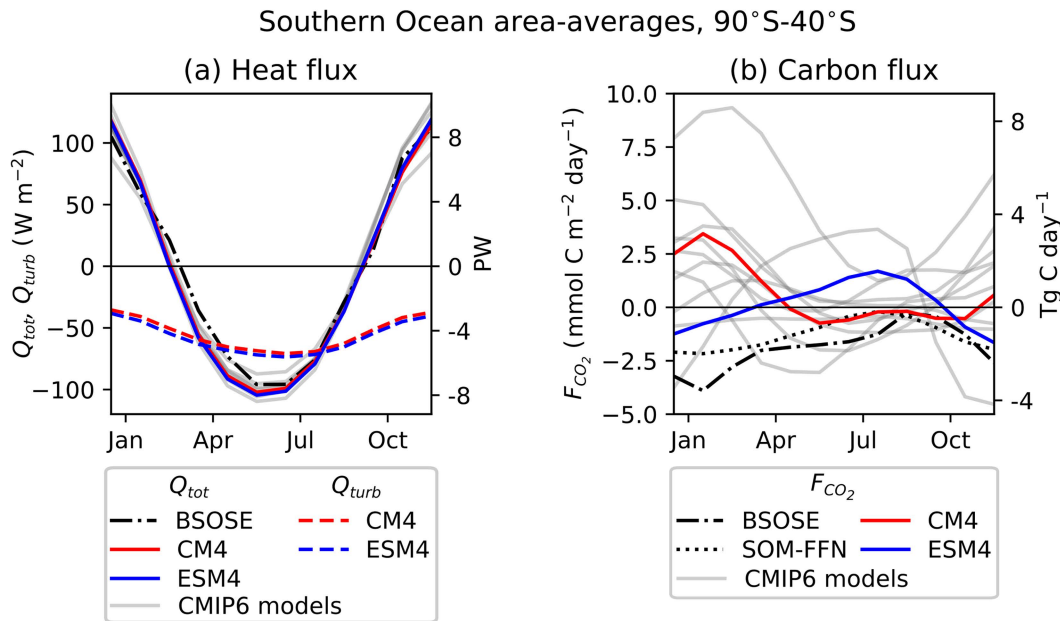


FIG. 2. Seasonal climatologies for (a) Southern Ocean total and turbulent heat fluxes and (b) CO_2 fluxes. Total heat fluxes include piControl simulations of GFDL models CM4 (solid red) and ESM4 (solid blue) alongside an ensemble of CMIP6 models (gray lines) and the B-SOSE assimilative ocean model from years 2013 to 23 (dashed–dotted line). Turbulent heat fluxes are included for CM4 (dashed red) and ESM4 (dashed blue). For carbon fluxes, the SOM-FFN reconstruction that includes BGC-Argo float data is also shown for years 1982–2017 (dotted line). For heat fluxes, positive values denote the fluxes into the ocean, while for CO_2 fluxes, positive values denote the fluxes out of the ocean. The total exchange in PW or $Tg C day^{-1}$ is included (right-hand axis) in which the area of the Southern Ocean south of 40°S is $7.65 \times 10^{13} m^2$.

synoptic meteorology (Soci et al. 2024). We use 6-hourly SLP snapshots, 10-m zonal and meridional wind snapshots, and 2-m air temperature snapshots to compare with CM4 and ESM4 output. While the data coverage used in ERA5 is greatly improved for years after 1980, the Southern Ocean and Antarctica remain some of the most poorly observed regions globally, with surface pressure measured less than once a day in many areas and near-surface winds measured less than once a month for most of the Southern Ocean (Soci et al. 2024). Thus, we present these results with the caveat that, for the Southern Ocean, ERA5 may include important biases due to its dynamics being less constrained by available observations.

c. Atmosphere and ocean composite creation

To visualize the storm response, we create composites of atmosphere and ocean fields in storm-relative coordinates. Using the storm centers identified by the algorithm, model fields are remapped bilinearly to great circle degrees away from the centers. Data within 10° of the storm center are then averaged across all tracked storms to create the composite response. Using the moving storm centers results in a Lagrangian-style composite that shows the near-instantaneous impact of a storm over a location and includes impacts of storms during the entire lifespan. In addition, we create composites that use the storm center locations at the time of the deepest SLP for each storm. By keeping these storm centers static for 10 days and using the aforementioned regridding, we can create Eulerian

composites that highlight the longer-term adjustment of the climate system after the passage of a storm. The atmospheric composites use snapshot data sampled at 6-hourly periods. For ocean data that are saved as daily averages from 0000 to 2359 UTC, the composites are created using the storm center location at 1200 UTC.

Storm anomaly composites are calculated relative to the daily climatologies of the piControl simulations. For context on how these anomaly fields are created, we present the seasonal climatologies of heat and carbon fluxes for CM4 and ESM4 alongside other CMIP6 preindustrial control model runs, the ocean assimilative model Biogeochemical Southern Ocean State Estimate (B-SOSE) (Mazloff et al. 2010; Verdy and Mazloff 2017), and the self-organizing map feed-forward neural network (SOM-FFN) reconstruction of carbon fluxes that includes BGC-Argo float data (Bushinsky et al. 2019) (Fig. 2). The climatological Southern Ocean heat flux is similar across the GFDL models and other models and reconstructions and is characterized by heat uptake over December–February (austral summer) and heat release over June–August (austral winter). Additionally, the GFDL models have similar seasonal turbulent heat fluxes (Fig. 2a, dashed lines), which are driven by the background wind fields.

The climatological Southern Ocean CO_2 flux, on the other hand, varies between the two GFDL models. The divergence within the GFDL models is reflective of the widespread in seasonal CO_2 fluxes in the Southern Ocean, with poor agreement

even on the time of year that the Southern Ocean releases CO₂ (Mongwe et al. 2018; Hauck et al. 2023). CM4 experiences CO₂ outgassing in summer and autumn and weak uptake from winter to spring, while ESM4 experiences outgassing in winter and uptake in summer. These differences in the integrated fluxes are caused mainly by a widespread outgassing throughout the Southern Ocean in summer for CM4, while ESM4 shows carbon uptake in the ACC region (Fig. S1 in the online supplemental material). The seasonality in preindustrial CO₂ fluxes for ESM4 is consistent with current data-based estimates, outside of a shift in magnitude expected from the lack of anthropogenic carbon in the ESM4 run. While the seasonality in CO₂ fluxes for CM4 is less consistent with the reconstructions, the behavior in CM4 is representative of current CMIP6 behavior for the Southern Ocean. This out-of-phase seasonal cycle in CM4 is consistent with an overly strong thermal component to ocean pCO₂ also found in other forced-ocean and coupled climate models (Mongwe et al. 2018; Hauck et al. 2023).

The large differences in the background seasonal cycles in CM4 and ESM4 may result from a variety of differences between the model, including parameterized high-latitude eddies changing vertical mixing rates (Russell et al. 2006; Gnanadesikan et al. 2015) and biological carbon uptake (Lévy et al. 2018) or model spinup time (Terhaar et al. 2024). Thus, by removing these climatologies from the storm anomaly fields, we can focus the composite analysis on storm-driven anomalies and dynamics within the models; without the climatology removal, wintertime storms in CM4 and ESM4 would be expected to have opposite signs in carbon fluxes because of their opposite seasonal cycles. While this separation neglects the role of subseasonal variability in setting seasonal variability (Whitt et al. 2019), it does allow us to examine how storm-induced anomalies may be related to their background seasonal cycles over the Southern Ocean.

Creating storm-centered composites from a long preindustrial control simulation also allows us to consider large ensembles of ocean and atmospheric variables and improve the signal-to-noise ratio in our analysis. As storm behavior can be diverse and the Southern Ocean is a region high in small-scale variability, these large ensembles allow for the isolation of storm impacts. For each model integration, the storm-following composites include around 800 000 6-hourly snapshots of atmospheric variables and 200 000 daily averages for each ocean variable. Composites that use the static storm centers for the Eulerian analysis include 50 000 regridded fields for each day poststorm.

3. Southern Hemisphere storm tracks and storm characteristics

While the Lagrangian storm tracker identifies storms through single points to represent the low pressure center, the wind fields associated with midlatitude storms have horizontal extents on the order of hundreds of kilometers. Thus, to avoid noise from interpolating moving centers onto the model grid and to better visualize the regions of the ocean potentially impacted by these midlatitude storms, we calculate storm-track

histograms using the method in Priestley et al. (2020), where values are in number of storm centers within a 5° great circle radius per month. The same storm can be included multiple times for this metric depending on its translation speed, so the storm density can be understood as an estimate of the number of storm days at that location. For reference, we include the equivalent storm-track histogram for the ERA5 reanalysis between 1979 and 2022 (Hersbach et al. 2020), with the caveat that the preindustrial scenarios in CM4 and ESM4 will not reflect climate warming signals like a poleward shift (Russell et al. 2006).

Both CM4 and ESM4 reproduce the salient features of the Southern Hemisphere storm tracks (Fig. 3), with the area-weighted pattern correlation between seasonal modeled and observed storm tracks over 0.96 for all model/season combinations. In the Southern Hemisphere, storms exist mainly between 40° and 65°S and shift seasonally alongside the prevailing westerlies. During summer, storms occur over a broad latitudinal band between 50° and 65°S, and most regions of the Southern Ocean experience 10–16 storm days per month. During winter, the storm track migrates toward the Antarctic coast and becomes more zonally asymmetric, with the highest storm activity in the Indian Ocean sector between 0° and 150°E. The storm track contains more storms in winter, with some regions experiencing over 20 storm days a month.

There are some differences in the storm-track behavior between the GFDL models and the ERA5 reanalysis due to the combination of model biases and the discrepancy in the forcing scenario (Fig. S2). During summer, CM4 and ESM4 experience more storm activity around 50°S and less storm activity near Antarctica, particularly near the Drake Passage and around 120°E. During winter, both CM4 and ESM4 experience storm activity biases relative to ERA5 in a zonal wave-number 3-type pattern. When these biases are zonally averaged, there is slightly more storm activity within the CM4 and ESM4 storm tracks during winter; the zonally averaged summer storm activity shows an equatorward bias in the storm-track location in CM4 and enhanced storm activity equatorward of the storm track for both CM4 and ESM4.

Our storm composites are created from all life stages of the tracked storms and thus show the long-term average storm conditions over the Southern Ocean. For simplicity, we present the composite storm conditions for CM4, as the composite storm properties are similar between CM4 and ESM4 (Fig. S3). We note that, because of the diversity of storm behavior and additional background variability, these composite magnitudes are generally small compared to the ensemble standard deviation. Despite their small magnitudes, the composites reveal simulated cyclone structures consistent with the classical Norwegian cyclone model (Bjerknes 1919; Fig. 4a).

The composite Southern Ocean storm has an associated SLP low that is 20 hPa lower than the surrounding SLP field (Fig. 4b). SLP anomalies are zonally symmetric, with a stronger pressure gradient to the north of the SLP low, reflecting the storms' relationship with the background latitudinal pressure gradient and generally higher SLP at lower latitudes. The storm-average wind vectors are aligned with this pressure gradient, and the average storm winds are 5 m s⁻¹ over their climatological values between 2° and 3° north of the storm

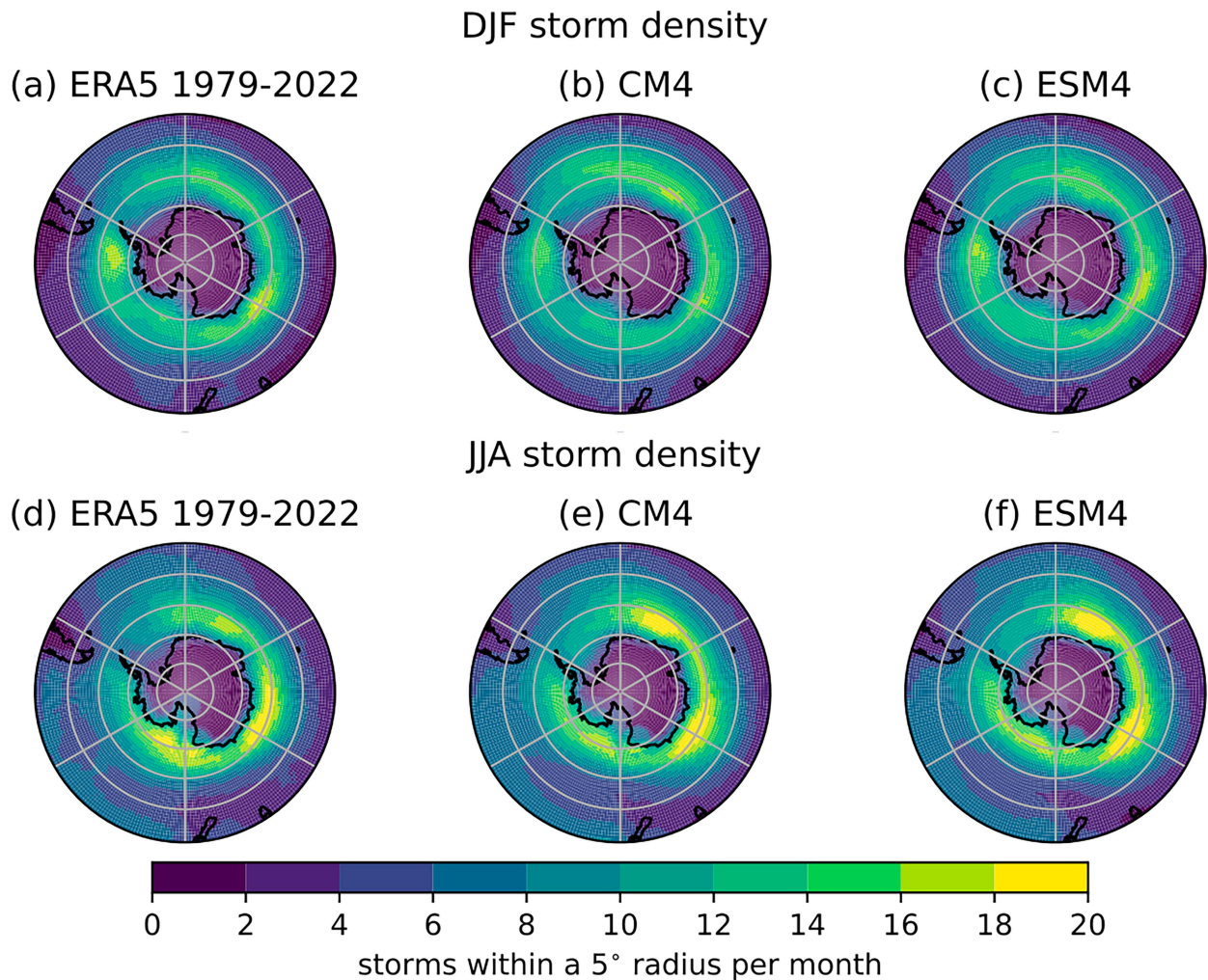


FIG. 3. Southern Hemisphere storm-track densities (number of storms per 5° spherical cap per month) for (top) austral summer (DJF) and (bottom) austral winter (JJA). The storm density is calculated using SLP from (a),(d) the satellite-era ERA5 output, (b),(e) CM4, and (c),(f) ESM4.

center, averaging total wind speeds of 12 m s^{-1} (Fig. 4c). South of the storm center, there is a mean easterly flow that overcompensates for the background westerly winds; compared to the mean wind fields, these regions experience slightly weaker wind speeds ($\Delta|u| < 1 \text{ m s}^{-1}$). Compared to the ERA5 reanalysis, the average model storm has a similar SLP gradient (a center-to-10°N SLP change of 25 hPa in the models versus 24 hPa in ERA5) and a maximum wind speed of around 1 m s^{-1} higher north of the storm center (Fig. S4). Additionally, the composites' surface air temperature anomalies are associated with how storms redistribute warm and cold airmasses. Surface air temperatures are anomalously warm on the eastern side of the storm, with a maximum of $+1.4^\circ\text{C}$ near the latitude of the storm center, associated with the location of northerly winds, and are anomalously cool with a minimum of -1.6°C on the western side of the storm associated with southerly winds (Fig. 4d).

Overall, the surface-based tracking algorithm shows a high level of consistency between the climatological storm tracks in CM4 and ESM4 with the ERA5 reanalysis fields. The storm

tracks in CM4 and ESM4 capture the large-scale features of storm activity in terms of both location and seasonality. Additionally, the average atmospheric characteristics of Southern Hemisphere storms are consistent with observations and follow midlatitude storm theory. While there remain biases in how the models represent storms over the Southern Ocean, these biases are likely small relative to current observational uncertainties in the Southern Ocean on seasonal time scales. The correspondence between CM4, ESM4, and ERA5 for these surface-based storm tracks indicates that the GFDL models are relevant for studying the impact of storms over the Southern Ocean: Their fully coupled setups allow for an internally consistent view of storms that have similar forcing features to those seen in the real world.

4. Storm impacts on heat and carbon fluxes

We continue by analyzing the surface air–sea fluxes of heat and carbon in the area around the storm centers by focusing on anomaly fields relative to the seasonal climatology. This focus

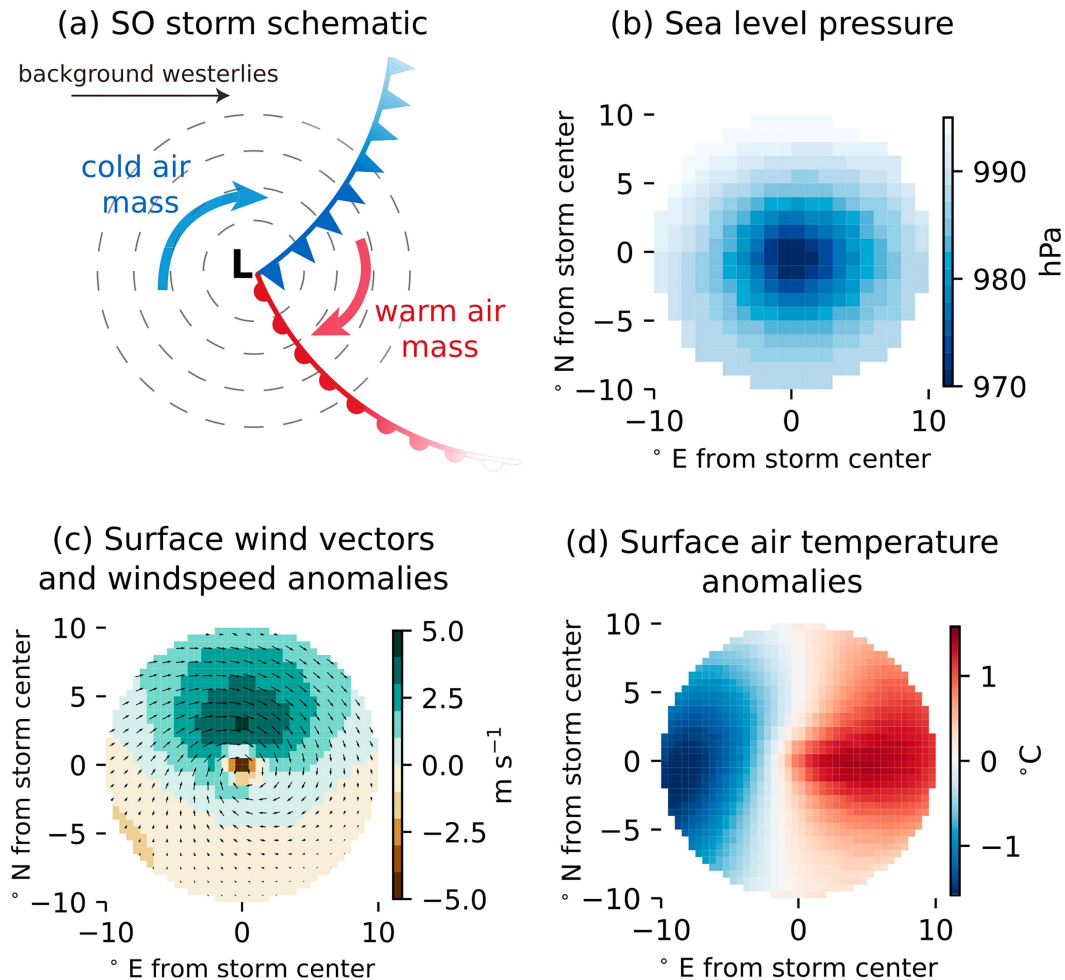


FIG. 4. (a) Idealized schematic of a mature Southern Hemisphere extratropical storm, with pressure contours, warm and cold fronts, and displacement of warm and cool airmasses. (b)–(d) CM4 storm-centered atmospheric composites of (b) SLP (hPa), (c) surface wind speeds (m s^{-1} ; colors) and vectors, and (d) surface air temperature anomalies ($^{\circ}\text{C}$). Distances are measured in great circle degrees away from the storm center.

inherently assumes that the seasonal cycles of heat and carbon fluxes are not driven by storm activity. While storm activity and subseasonal forcing can impact longer time-scale ocean properties (Whitt et al. 2019), the seasonal cycles of heat and carbon are driven primarily by radiative forcing, mean wind-driven circulation, and biological activity (Lenton et al. 2013). While the storm anomalies for any one storm snapshot will include a wide range of nonstorm-related variability, we expect the large ensemble of storm snapshots to smooth over variability from other sources. We do note that the more frequent recurrence of storms in the winter months (Fig. S5) results in all-storm-average conditions that are more reflective of wintertime storm conditions, although storms are found to occur at all times of year.

Heat flux anomalies (Figs. 5a,b) align with the frontal structure of a classical midlatitude storm: The ocean releases heat to the atmosphere on the western flank consistent with the location of the cold airmass (with a minimum heat flux anomaly from -48 to -50 W m^{-2}), while there is a smaller region where the ocean takes up heat from the warmer airmass on

the eastern flank (with a maximum heat flux anomaly of $25\text{--}27 \text{ W m}^{-2}$). The models have very similar patterns of anomalous heat uptake and release, with a pattern correlation of over 0.99. The overall flux of heat is from the ocean to the atmosphere, with an area-average anomalous heat flux of -11.4 W m^{-2} in CM4 and -10.3 W m^{-2} in ESM4. Storms additionally induce an anomalous flux of CO_2 from the ocean to the atmosphere (Figs. 5c,d), consistent with carbon outgassing found in Waveglider and BGC-Argo storm studies (Nicholson et al. 2022; Carranza et al. 2024). Again, the models show virtually the same pattern of anomalous carbon fluxes, with a pattern correlation over 0.99. The anomalous outgassing of CO_2 is the strongest just north of the storm center and reaches a maximum of $2.0 \text{ mmol C m}^{-2} \text{ day}^{-1}$ in CM4 and $1.8 \text{ mmol C m}^{-2} \text{ day}^{-1}$ in ESM4. This region of the largest CO_2 outgassing is consistent with the region of highest winds, including the background westerlies, under which enhanced wind-driven mixing can effectively entrain deeper waters with higher DIC into the mixed layer and then quickly equilibrate

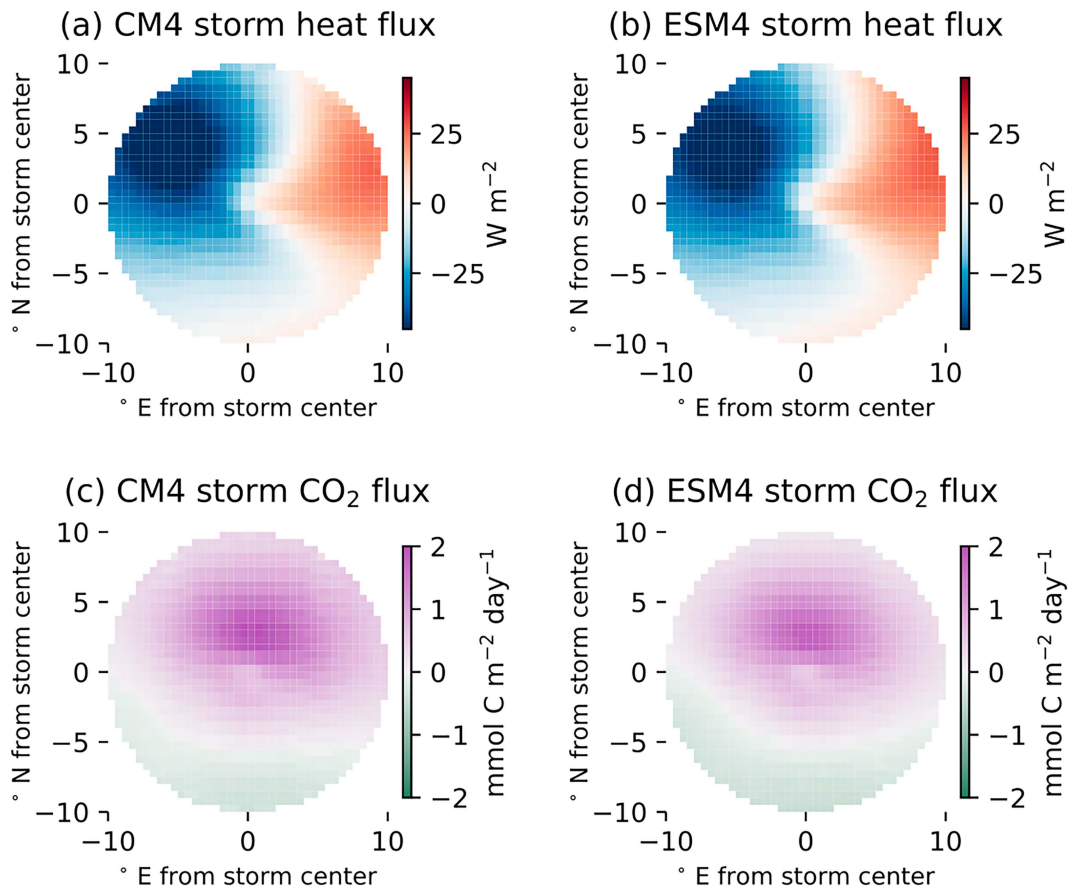


FIG. 5. GFDL storm-centered composites of atmosphere–ocean flux anomalies relative to the daily climatology: (a),(b) heat fluxes (W m^{-2}) for CM4 and ESM4, and (c),(d) CO_2 fluxes ($\text{mmol C m}^{-2} \text{ day}^{-1}$) for CM4 and ESM4. For heat fluxes, positive values indicate the fluxes of heat into the ocean. For carbon fluxes, positive values indicate the fluxes of carbon out of the ocean. Distances are measured in great circle degrees away from the storm center.

that high-carbon water with the atmosphere. At the southern flank of the storm, the weaker easterly winds are associated with slight anomalous carbon uptake, which is consistent with the CESM results in Carranza et al. (2024) but not found in the study's BGC-Argo analysis. Overall, the area-average anomalous outgassing underneath Southern Ocean storms is $0.50 \text{ mmol C m}^{-2} \text{ day}^{-1}$ for storms in CM4 and $0.38 \text{ mmol C m}^{-2} \text{ day}^{-1}$ for storms in ESM4. The local anomalous fluxes associated with storms are approximately 25%–50% of the Southern Ocean climatological heat fluxes and can reach the same order of magnitude as the climatological CO_2 fluxes in Fig. 2, although the compensating patterns of these signals result in storm-average anomalies that can be an order of magnitude smaller than the climatological heat and carbon fluxes.

a. The climatology of storm heat and carbon anomalies

The heat flux and carbon flux anomaly composites presented above include storms at all locations within our domain and at all times of the year. As there are both regional shifts of storm activity throughout the year and highly regional background seasonal cycles for heat and carbon, these

full composites may obfuscate important seasonal variability within the storm anomalies. Thus, we proceed by exploring how storm-driven heat and carbon anomalies vary throughout the course of the year.

Anomalous heat and CO_2 fluxes associated with storms exhibit seasonality, which can be seen through a “storm anomaly climatology” (Figs. 6a,b). Here, anomalous fluxes are sorted by the day of year and area-integrated to account for both seasonal changes in the number of storms and seasonal patterns in the anomalous fluxes. When integrated over the entire Southern Ocean, storms induce an anomalous release of heat and CO_2 throughout the year, with an exchange of heat ranging from -0.05 to -0.31 PW and an exchange of CO_2 ranging from 0.02 to $0.32 \text{ Tg C day}^{-1}$. The storm-induced heat release is similar between CM4 and ESM4, with the maximum anomalous release of heat occurring in summer, a minimum heat release centered in autumn, and a local maximum in heat release in winter.

Conversely, the storm-induced anomalous release of CO_2 is model dependent in terms of its seasonal phasing and variability. In CM4, the storm-induced exchange reaches its maximum in late summer and early autumn and reaches its minimum

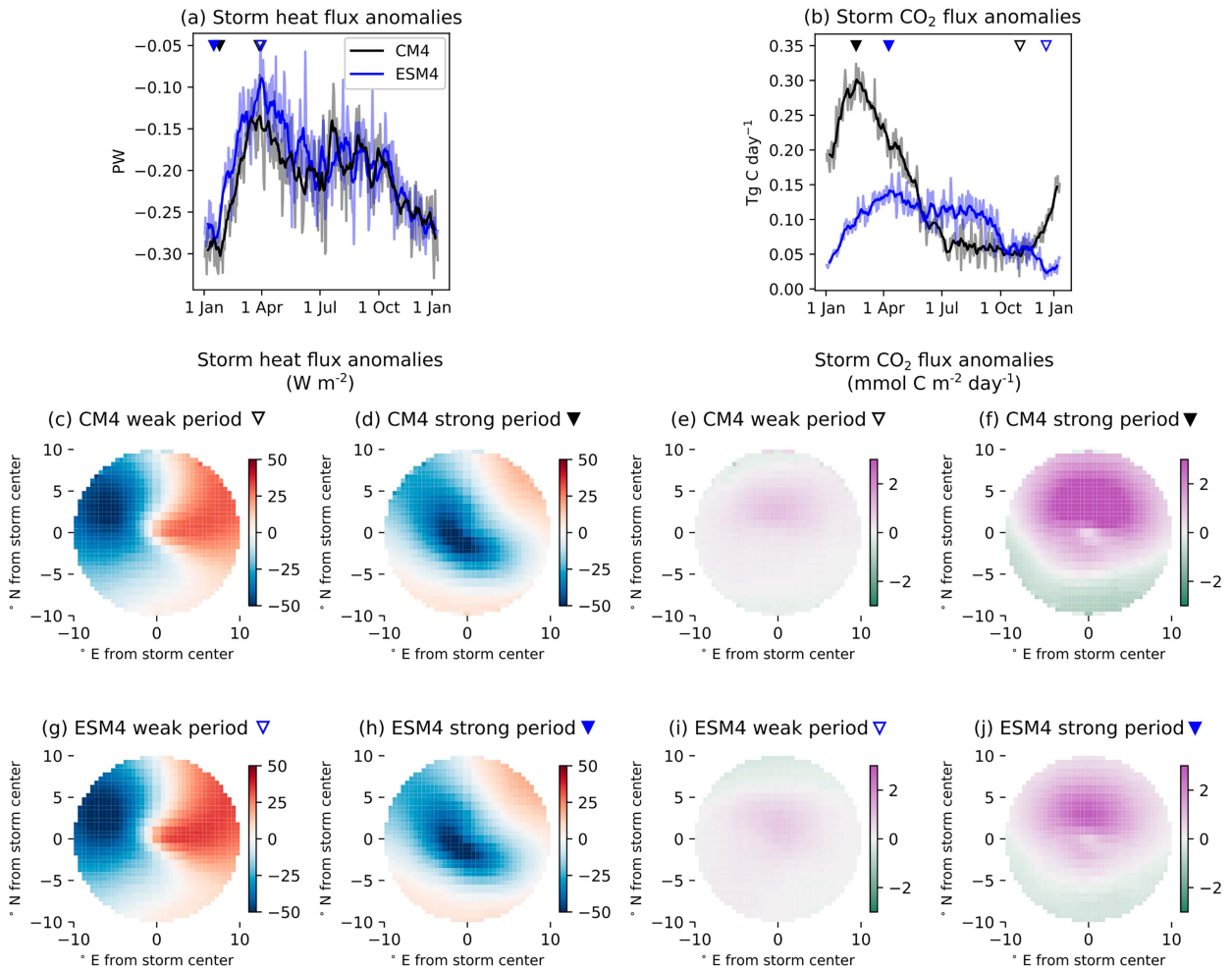


FIG. 6. Yearly climatology of (a) integrated storm heat flux anomalies and (b) CO₂ flux anomalies for Southern Ocean storms in CM4 (black) and ESM4 (blue). Daily averages are calculated for each day of the year for light lines, with 10-day rolling average in dark bold lines. Periods of the year with the highest (lowest) heat and CO₂ release are marked with filled (unfilled) triangles in the corresponding model color. (c)–(j) Average storm anomalies for strong and weak flux periods for CM4 and ESM4 heat and CO₂ fluxes. Strong and weak periods are defined as the 31-day mean centered around the day of the year with maximum (minimum) fluxes as shown in (a) and (b). For heat fluxes, positive values indicate the fluxes of heat into the ocean. For carbon fluxes, positive values indicate the fluxes of carbon out of the ocean.

over late winter. In ESM4, the storm-induced exchange reaches its maximum in autumn and reaches its minimum in summer. The range of the storm-induced CO₂ exchange over the course of the year is also over twice as large in CM4 as in ESM4. The storm climatology of CO₂ fluxes shows more seasonal variability than the storm climatology of heat fluxes, likely as the integrated heat fluxes involve the compensation of ocean areas with anomalous heat uptake and heat release, whereas the spatial pattern of CO₂ fluxes is dominated by the region of anomalous outgassing.

To illustrate the variability in storm-associated fluxes throughout the year, we compare the anomalous flux composites from storms associated with the periods of maximum and minimum heat or carbon release within the storm anomaly climatology for each of the models (months centered around the dates marked in Figs. 6a,b). We define these

periods of the year with maximum fluxes of heat or carbon out of the ocean as “strong” and the periods of the year with minimum fluxes of heat or carbon out of the ocean “weak,” and these periods are defined for each tracer and model separately. For heat fluxes, periods of relatively weak storm-driven heat release are defined by a larger area east of the storm center where the ocean takes up heat from the atmosphere (Figs. 6c,g); periods of relatively strong storm-driven heat release, in comparison, show a weaker region where the ocean releases heat but a much smaller region of heat uptake (Figs. 6d,h). Conversely, there is a consistent structure within the CO₂ fluxes during periods of weak and strong CO₂ release. The regional pattern of CO₂ fluxes during periods of strong storm-induced release is, to first order, a magnified version of the fluxes during periods of weak storm-induced release (Figs. 6e,f,i,j). This amplification is stronger in CM4 than

in ESM4, resulting in a larger variation within the storm anomaly climatology.

b. Relationships between storm-induced fluxes and the background seasonal cycle

Despite the fact that the storm composites use anomalies relative to the seasonal cycle, the seasonalities in the storm composites have a high level of correspondence with the seasonal cycles. We synthesize this correspondence by correlating the daily climatologies of heat and carbon fluxes (Fig. 2) with the 10-day rolling average storm-induced fluxes (Fig. 6) to ignore the noise inherent in the daily storm climatology from the immediate insertion and removal of centers into the storm mask.

The storm-driven heat fluxes in CM4 and ESM4 are negatively correlated with the climatological heat fluxes ($r = -0.60$ for CM4; $r = -0.55$ for ESM4). The storm-driven carbon fluxes in CM4 and ESM4 are positively correlated with climatological carbon fluxes, but the strength of the carbon correlations is highly model dependent. The correlation between CM4 storm and background carbon fluxes is high ($r = 0.93$), indicating close to a one-to-one relationship between background fluxes and strength of storm outgassing. In comparison, ESM4 has a more modest positive correlation between storm and background carbon fluxes ($r = 0.59$).

ESM4 additionally exhibits a correlation between its storm heat and storm carbon flux anomalies ($r = 0.66$), which is not found in CM4. Because of the change in sign between heat and carbon fluxes going from the ocean to the atmosphere, this positive correlation reflects an inverse relationship, where the strongest carbon outgassing occurs at the same time of the year with the weakest heat fluxes from the ocean to the atmosphere. Thus, despite the fact that storm-driven heat and carbon fluxes have different horizontal structures and the seasonal variation within the horizontal structure differs between heat and carbon, with ESM4, there is a consistency in the bulk impact of storms on heat and carbon throughout the year.

5. Poststorm adjustment of air–sea fluxes

As anomalous fluxes at each location, by definition, sum to zero over the course of the climatology, the anomalous air–sea fluxes of heat and carbon in the presence of a storm are matched by opposing fluxes during nonstorm periods. The Lagrangian view of storm anomalies used above cannot easily provide a sense of how air–sea fluxes behave once a storm has passed. To better understand the ocean response, we switch to an Eulerian framework. For Eulerian composites, we identify the time and location at which each storm reaches its lowest SLP. The day that the storm reaches that SLP is denoted as day 0, and the storm mask is kept constant at that location for the following 10 days, denoted as days 1–10. The choice to use the time of the lowest SLP for each storm was made to reduce the computation time; even with this limitation, our composites consist of around 50 000 snapshots for each day poststorm.

Air–sea flux anomalies of both heat (Fig. 7) and carbon (Fig. 8) are quickly reduced within 2–3 days after the passage

of the storm. The composite fluxes 1 day after the strongest low pressure reflect the eastward propagation of an average cyclone (see SLP in Fig. S6); by 2 days after the storm, there is little signal of any remaining low pressure system due to the systems moving outside the original 10° radius and the uncertainty in the exact displacement of the storm center. The Eulerian composites of atmospheric variables show no re-emergence of atmospheric storm-like signals over the 10-day period during and after the storm, indicating that in spite of the continual presence of storms, the uncertainty in the location of the next storm is large enough that composites reflect the storm present at $t = 0$ days.

Heat fluxes at $t = +1$ day after the passage of a storm (Fig. 7) are dominated by the cold sector of the storm, as the eastward propagation of the storm along the background westerlies means that the original storm center is located beneath the perturbed cold airmass (Fig. 4a). By $t = +2$ days, there is a weak flux of heat out of the ocean ($> -10 \text{ W m}^{-2}$) throughout the domain. The poststorm heat fluxes are generally similar between CM4 and ESM4, although the heat flux between 1 and 2 days poststorm is more negative in ESM4 by $\sim 2 \text{ W m}^{-2}$. Conversely, the carbon fluxes after the passage of a storm (Fig. 8) weaken into a meridional dipole with continued outgassing north of the original storm center and carbon uptake south of the storm center. The carbon signals are marginally stronger in ESM4 than in CM4, but overall, the two models show a high level of correspondence.

The area-average poststorm fluxes (Fig. 9) show seasonality that contrasts with the seasonality found in the Lagrangian storm impacts in section 3. Heat fluxes are most negative 1 day poststorm over most months of the year, and in particular in austral winter, as when the storm moves east, a larger fraction of the mask is influenced by the equatorward transport of cold air. The poststorm heat release is most persistent in winter for both models, and in summer, both models show a weak rebound to heat uptake that begins 4–5 days poststorm. Carbon fluxes poststorm show that the dampening of the $t = 0$ -day signal is consistent across all months, and the compensation within the dipole leads to near-zero fluxes soon after the storm passes. Interestingly, in CM4, there is a continued weak outgassing from 2 to 10 days poststorm from autumn to spring, and a weak rebound to carbon uptake centered around the winter season; for ESM4, there is not a clear seasonality in the longer-term adjustment.

6. Discussion and conclusions

In this study, we have explored the seasonal climatology of storm-induced heat and carbon fluxes in the Southern Ocean. Storms are continuously present throughout the Southern Ocean and can induce strong anomalous air–sea fluxes through changes in wind speed and air–sea gradients. Recent storm studies have employed ocean-only model runs, which assume a passive role for the ocean, preclude the analysis of heat fluxes, and include signals from present-day anthropogenic warming. Using two fully coupled climate models integrated under preindustrial conditions, our study complements current work by providing the coupled response and a view of storms' natural role in the cycling of carbon and heat. Our study provides both storm-following Lagrangian composites

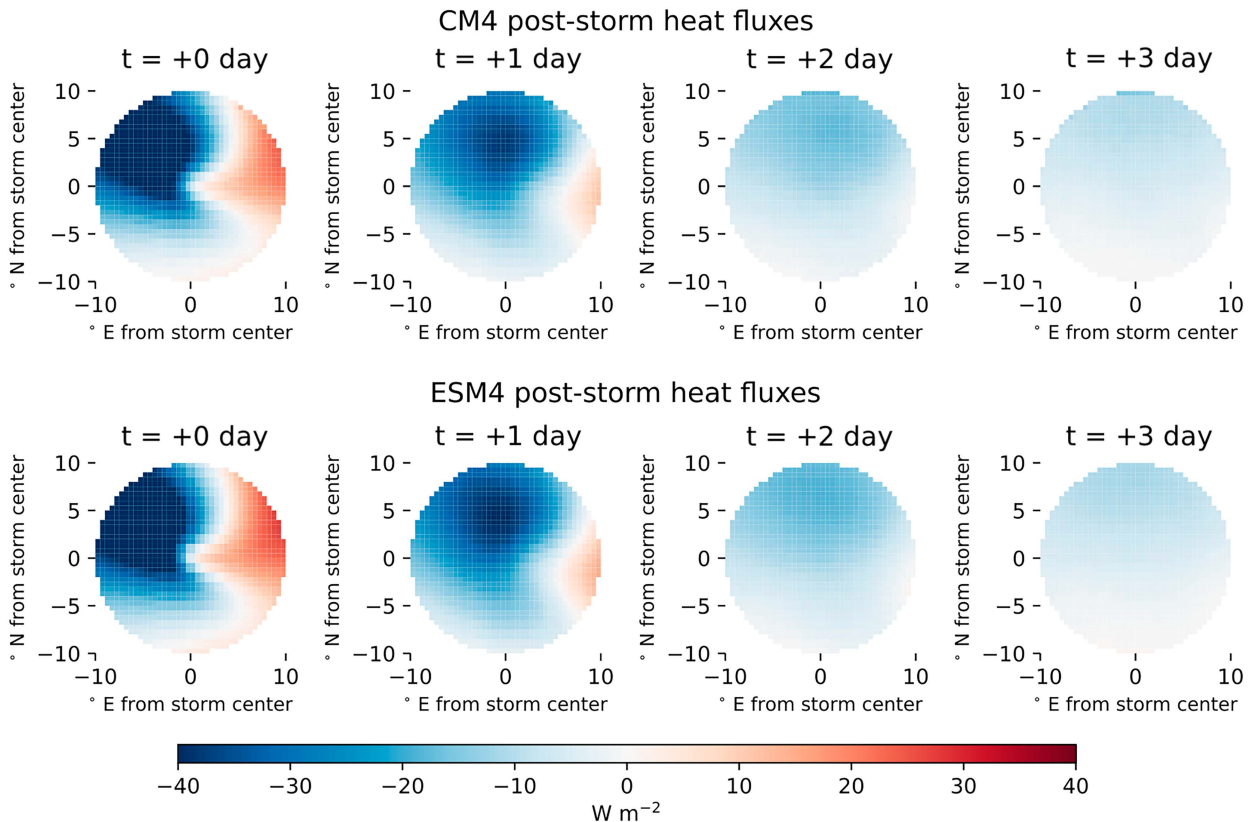


FIG. 7. Eulerian heat fluxes (W m^{-2}) at the location of each storm's peak for (top) CM4 and (bottom) ESM4, calculated as the time when the storm attains its lowest SLP ($t = +0$ day), at $t = +1$ day, $t = +2$ days, and $t = +3$ days after the peak of the storm. Positive values indicate the fluxes of heat into the ocean.

and Eulerian impulse-response composites to explore the spatial patterns and seasonality of the instantaneous response of ocean heat and carbon fluxes, as well as their poststorm adjustment.

We find that storms in the Southern Hemisphere drive a net release of both heat and carbon fluxes from the Southern Ocean, with distinct spatial patterns reflecting the storms' conveyor belts and wind speeds, respectively. The storm-driven heat release is the strongest in austral summer, while the storm-driven carbon outgassing peaks in austral summer in CM4 and austral autumn in ESM4. Both heat and carbon fluxes are dampened within days after the passage of a storm across all months of the year. Storm-driven heat fluxes are more persistent than carbon fluxes, with storm-driven heat fluxes being the most persistent in the austral winter. Overall, although the net average ocean response to storms is highly similar between the two models, there is a large amount of variability in the ocean response to storms, both under individual storms and when considering the seasonal progression of those responses.

a. Using global coupled models for storm studies

The CM4 and ESM4 Southern Hemisphere storm tracks, as measured by local sea level pressure minima, show a high correspondence with the present-day track in the ERA5 reanalysis.

The models replicate major features of the storm track such as the latitudinal band, the contraction of the storm track toward Antarctica in austral winter, and the hotspots of storm activity in the Indian–Pacific sector of the Southern Ocean.

Coarse-resolution atmospheric models in CMIP6 have been found to have equatorward biases for their Southern Hemisphere storm tracks (Priestley et al. 2023) and too shallow SLP lows (Priestley and Catto 2022a). Thus, it is possible that, by using a fully coupled model, biases in storm activity lead to ocean composites that are dampened and biased toward the subtropics. However, we note that, while this bias has been related to sea surface temperature biases, ESM4 has a more equatorial storm track in spite of its warmer sea surface temperature biases over much of the Southern Ocean (Dunne et al. 2020a). The equatorward shift in the westerlies in ESM4 has been attributed to sea salt aerosol representation, highlighting the complexities in achieving an adequate representation of the storm track.

As the Southern Ocean remains undersampled and models show low levels of agreement for the mean ocean state (Johnson et al. 2017; Fox-Kemper et al. 2021), we believe that the biases in the storm-track locations and intensity likely play a small role in setting the spread of the modeled storm responses. Indeed, despite the differences in the storm track between CM4 and ESM4,

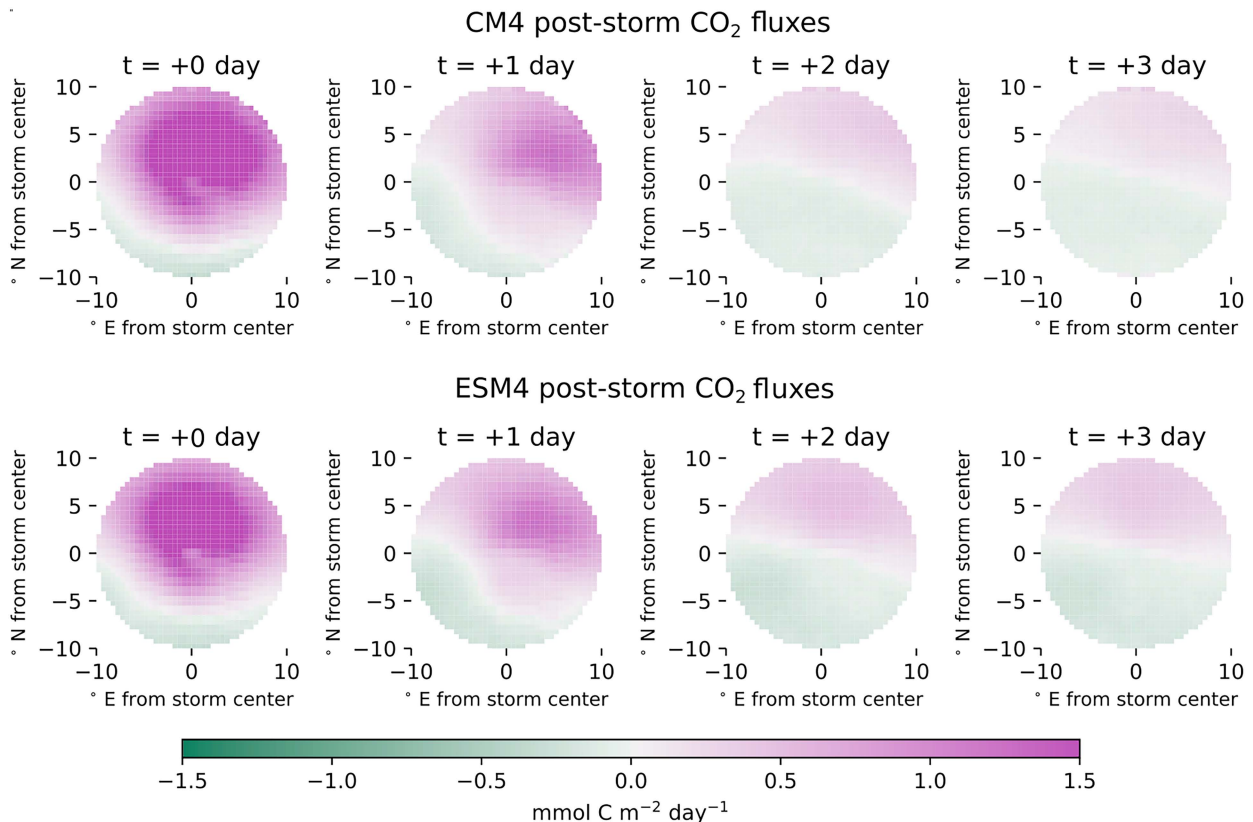


FIG. 8. Eulerian carbon fluxes ($\text{mmol C m}^{-2} \text{ day}^{-1}$) in the same layout as in Fig. 7. Positive values indicate fluxes of carbon out of the ocean.

the models show near-identical storm heat fluxes, indicating a level of robustness outside these errors. Fully coupled climate models like CM4 and ESM4 are thus important tools to understand both the current state of storm-induced variability and the future role of storms in setting the climate in a warming world. However, features such as the zonal wave-number-type biases in the winter storm-track location could have important implications for processes like mode water formation, which occurs in quite localized regions within the Southern Ocean (Li et al. 2021). Further work is required to understand the relationship between storms and ocean ventilation with careful consideration on the zonal patterns in winter storm activity, including with higher-resolution atmosphere and ocean models.

We note that both CM4 and ESM4 have relatively coarse horizontal resolutions, particularly when considering high-latitude ocean dynamics. Unresolved ocean mesoscale and submesoscale features can modulate the storm-driven heat and carbon responses explored here in a variety of ways; for instance, eddies can impact both surface winds through their sea surface temperature anomalies (Frenger et al. 2013) and surface carbon fluxes and concentrations through isopycnal heave (Keppler et al. 2024). As these small-scale features can alter both the atmospheric and oceanic components of the storm response, future work with higher-resolution models

and observations will be necessary to understand how these various impacts compensate or feed back into storm-induced fluxes.

b. Anomalous heat and carbon fluxes from storms

On average, storms lead to a release of heat and carbon from the ocean to the atmosphere. The average Southern Ocean storm within the GFDL models is associated with anomalous fluxes of -0.035 PW and $0.020 \text{ Tg C day}^{-1}$ from the ocean, leading to an annual average heat flux of -0.2 PW and an annual average carbon flux of 40 Tg C yr^{-1} . The storm-induced outgassing diagnosed in the GFDL models is consistent with Nicholson et al. (2022) and Carranza et al. (2024), and the GFDL models lie between the outgassing estimates from CESM and BGC-Argo of Carranza et al. (2024). The structure of storm-driven CO_2 outgassing in CM4 and ESM4 is similar to that in CESM, although CM4 and ESM4 have stronger outgassing (2 and $1.8 \text{ mmol C m}^{-2} \text{ day}^{-1}$ in CM4 and ESM4 versus $1.5 \text{ mmol C m}^{-2} \text{ day}^{-1}$ in CESM2). All models differ from the outgassing pattern in BGC-Argo floats in a similar fashion, with models showing a region of carbon uptake south of the storm center that is not found in the float-based composites, although this discrepancy may also be sensitive to the sampling density of the floats. The composite heat and carbon anomalies align with first-principle

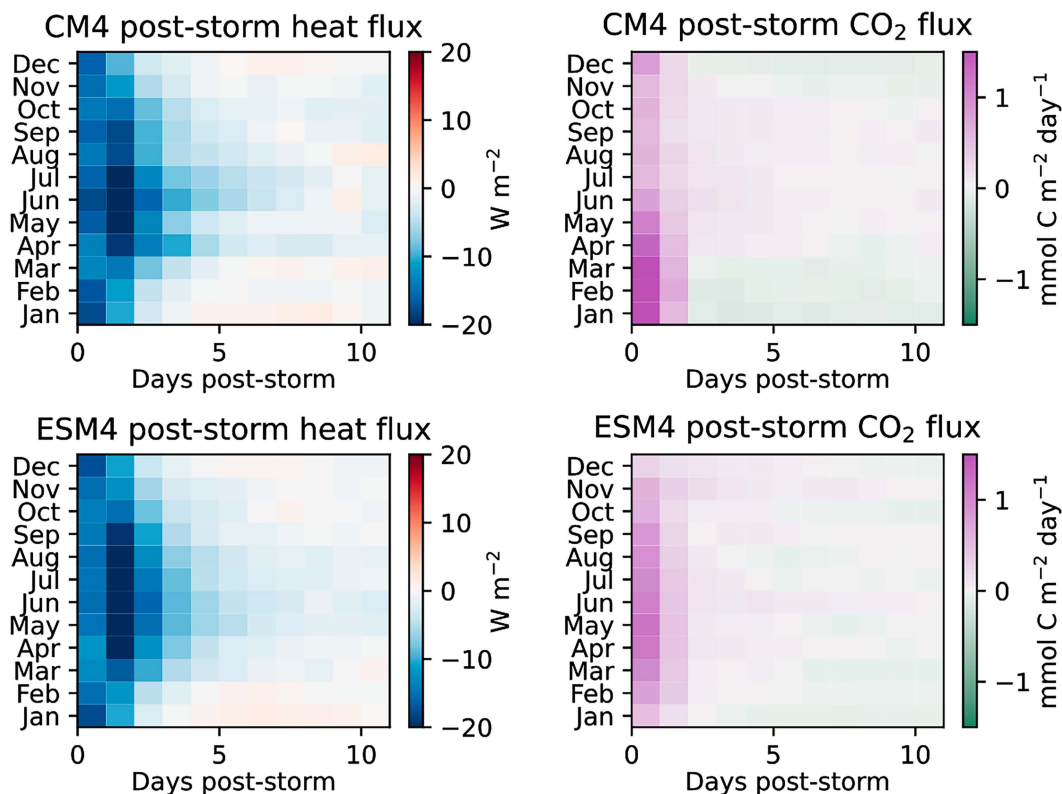


FIG. 9. Storm-area-average fluxes of (left) heat and (right) carbon for storms in (top) CM4 and (bottom) ESM4. Days are 0–10-day postpeak storm, with the storm peak defined as in Fig. 7. Positive values indicate the fluxes of heat into the ocean and fluxes of carbon out of the ocean.

characteristics of extratropical storms, with regions of ocean heat uptake (release) aligning with the displaced warm (cool) airmasses within the storm and the regions of the highest carbon outgassing aligning with the regions that have the highest winds and thus most wind-induced ocean mixing. These anomalous heat and carbon fluxes are locally large, which emphasizes the importance of capturing these extreme events within observations for an accurate time series view of Southern Ocean surface fluxes.

Compared to the seasonal climatology of heat and carbon throughout the Southern Ocean, the climatology of storm heat and carbon anomalies integrated under the storm-affected area is relatively small; peak storm heat flux anomalies of -0.3 PW are less than 4% of the peak seasonal heat flux throughout the year, and peak storm carbon flux anomalies of 0.12 – 0.3 Tg C day^{-1} are between 5% and 10% of the peak seasonal carbon flux throughout the year (Figs. 2a,b and 6a,b). However, the storm-induced flux anomalies systematically release heat and carbon from the ocean to the atmosphere, while the background seasonal cycles of heat and carbon have large signals of opposite sign that largely compensate on annual time scales. Because of their contrasting background seasonal cycles, the annual anomalous carbon release from storms is about 25% of the net Southern Ocean flux in CM4 (50 vs 200 Tg C) and the same order of magnitude of the net Southern Ocean flux in ESM4 (with both

around 33 Tg C). For heat fluxes, the annual average heat flux in the preindustrial control simulations is near -0.4 PW, resulting in storm anomaly fluxes that are approximately half. Considering that the average storm covers approximately 3 million km^2 or approximately 4% of the ocean south of 40°S , these anomalous fluxes associated with storms are highly localized features that play an important contribution to understanding the annual cycling of carbon and heat in spite of their relatively small roles in setting basinwide instantaneous fluxes.

The estimated heat and carbon fluxes from Southern Ocean storms presented here is a lower bound, as by removing the daily climatology from our signals, we exclude the interaction between storm anomalies and mean seasonal fluxes. When considering the coupled heat and carbon response, the separation of seasonal and synoptic fluxes is complicated by the fact that turbulent heat fluxes and gas exchange are parameterized as different powers of wind speed. Further work is required to better understand the extent to which synoptic variability feeds back into longer time scales of heat and carbon exchange.

c. The re-emergence of seasonal signals due to storm activity

Storm-induced fluxes of heat and carbon exhibit seasonal variability that leads to different periods of maximum heat and

carbon release from storms. In both CM4 and ESM4, the maximum storm-induced heat release occurs in austral summer. For storm-induced carbon outgassing, our results are model-specific; CM4 experiences its maximum carbon outgassing in summer, while ESM4 experiences its maximum carbon outgassing in autumn. The seasonalities of storm heat and carbon fluxes are significantly correlated with the background seasonal signals, with storm heat fluxes anticorrelated with the seasonal heat fluxes and storm carbon fluxes positively correlated with seasonal carbon fluxes.

Seasonality in storm-induced carbon fluxes was also found in Carranza et al. (2024) for both CESM and the BGC-Argo floats, with CESM storm-induced outgassing peaking in austral spring and BGC-Argo storm-induced outgassing peaking in austral winter. Thus, with the inclusion of the GFDL models, current analyses can be found to support peak storm fluxes at any season, underlining the large uncertainty that continues to exist in terms of synoptic-scale variability of heat and carbon uptake.

d. Potential drivers of seasonal storm fluxes

A key result of our work is a re-emergence of a seasonal signal for both heat and carbon fluxes, as this study by construction explores storm anomalies from the seasonal cycle. Such a re-emergence occurs because of nonrandom sampling of the anomaly fields. Nonrandom spatial sampling may result in the re-emergence of some seasonality as the storm track contracts toward Antarctica in the austral winter, and sea ice coverage expands, providing a barrier for air–sea fluxes. The role of sea ice–covered regions is likely minimal as most Southern Ocean storms occur over the open ocean, although storm composites in high-ice regions do show dampened heat and carbon fluxes (Fig. S7).

Seasonal changes in storm properties, particularly wind speed and surface pressure, may also induce seasonality in air–sea fluxes. However, the seasonal heat and carbon fluxes found in CM4 and the seasonal heat fluxes in ESM4 do not align with seasonal changes in storm properties, as the deeper lows, stronger winds, and enhanced temperature gradients during wintertime storms would act to enhance rather than dampen fluxes from the ocean. Thus, while the all-storm composites of anomalous heat and carbon fluxes reflect the atmospheric drivers of storm signals, how those signals manifest throughout the year must be related to the underlying oceanic properties.

The correspondence between the background seasonal cycles and storm-driven anomalies suggests that the background ocean state plays a role in setting the seasonal storm signals. For instance, summertime shallow mixed layers and strong stratification at the base of the mixed layer could allow for little communication between the mixed layer and thermocline, and mixing from storms could allow for the enhanced release of thermocline heat and carbon, resulting in the summertime maxima seen in CM4. The opposing vertical gradients in ocean heat and carbon could then correspond with the change in the sign of correlation between storm-driven and background seasonal signals. Seasonal changes in the mixed layer depth, stratification,

biological processes, and age of waters below the pycnocline could also result in the CM4 behavior of enhanced carbon fluxes in the summer. It is likely a compensation of controls, including mixed layer depths, stratification, and ocean age, set the seasonality of storm fluxes. Further work is necessary to decompose the seasonal cycle into the various physical drivers, taking coupled dynamics into account. We speculate that these drivers will be sensitive to the regional structure in the atmosphere and ocean circulation as well as ocean biogeochemical regimes, which may result in relatively small changes between models or observations, resulting in larger differences in the emergent seasonal behavior.

Last, ocean biology may play a role in the shift in seasonality between models. While both CM4 and ESM4 have ocean biogeochemistry models included, the CM4 biogeochemistry model BLING is highly idealized and has diagnostic biological processes, while the ESM4 biogeochemistry COBALT has a larger set of tracers and includes explicit phytoplankton types for biological carbon drawdown. We speculate that the shift in seasonality in ESM4 relative to CM4 could arise from biological drawdown of carbon driven by the upwelling of nutrients that partially offsets an outgassing signal from the entrainment of deep waters. While diagnosing the parts of the biogeochemistry models that contribute to these signals is complex and outside of the scope of the current study, future work on the drivers of this seasonality may provide further insights into the degree of physical versus biological control on the storm carbon anomalies. Ocean observations will be important to include for this process understanding, as Southern Ocean carbon fluxes arise from a combination of thermal and nonthermal controls, and ocean models have a wide range of uncertainty in terms of these controls.

This work highlights the complexities in understanding the drivers of storm-induced ocean fluxes across time scales. The models have similar average storm imprints on heat and carbon flux anomalies that suggest similar atmospheric drivers. However, it is still unclear whether the seasonal differences between the models arise from the same mechanisms that have distinct background seasonalities or if they arise from model-dependent mechanisms. We speculate that these signals arise from a complex compensation between atmospheric and oceanic drivers, which would allow for relatively small changes between models or discrepancies between models and observations to manifest into larger differences seasonally. Further work is required to understand these drivers, with careful consideration about how single storms and storm tracks feed back into long-term mean behavior across the Southern Ocean.

e. Implications for the current and future role of storms in the Southern Ocean

Our analysis provides a climatological perspective for how short-lived weather systems with strong winds and fronts can impact the Southern Ocean, but we do not consider how storms operate under external forcing or interannual variability. Changes in both the atmosphere and the ocean will cause

both the storm tracks and the Southern Ocean storm response to evolve in a warming climate. It is necessary to understand the impact of these changes as the Southern Ocean plays a dominant role in the present-day uptake of anthropogenic carbon and heat, which modulates the global climate response to emissions.

One major implication of the climatological work presented here is that individual aspects of future climate change may impose contrasting signals onto storm-driven anomalies. These signals will arise from a combination of changing storm properties, storm locations, and ocean properties. For instance, extratropical storm tracks are expected to move poleward under continued warming, with fewer storms but more extreme wind speeds (Priestley and Catto 2022b; Gentile et al. 2023). Heightened wind speeds and decreased storm density may enhance the outgassing underneath individual storms, even if the cumulative storm-induced outgassing were to remain unchanged. Conversely, the decrease in the baroclinicity of storms from polar amplification in surface warming may decrease the frontal structure seen in storm-induced heat fluxes.

In addition, the ocean uptake of anthropogenic heat and carbon alters vertical gradients within the Southern Ocean. The change to vertical gradients will change how ocean mixing from storms controls anomalous heat and carbon fluxes, as the entrainment of older and deeper waters may, for instance, lead to smaller changes in surface carbon concentrations if the mixed layer already has additional carbon. These changes in the atmosphere and ocean will also have regional variations, which have the potential to change the regional drivers of storm responses and potentially feed back into the storm anomaly climatologies. Thus, in addition to understanding the drivers of the seasonal cycles found in this work, we will also extend our work to historical and future climates to understand how these atmospheric and oceanic changes combine for future storm signals.

As the relationship between storm-driven fluxes to each other and their relative seasonal climatologies is highly uncertain, future work will also explore the mechanisms behind the oceanic response to storms, which are necessary to better understand the true role of storms within the Southern Ocean climate. These mechanistic studies will require the continued use of models alongside available observations, as the density of observations and the near-constant presence of storms in the Southern Ocean will require careful consideration on how storm signals alias into seasonal signals.

In conclusion, we have presented storm-centered composites of atmosphere–ocean fluxes for a long preindustrial run of two fully coupled climate models. Storms induce large local anomalous fluxes of heat and carbon in the Southern Ocean, leading to net release of heat and carbon from the ocean. The mean anomalous fluxes are highly similar between models, which reflects a top-down control from the atmosphere on the bulk ocean response. Despite similarities in the bulk storm activity and all-storm-average flux anomalies between models, the seasonality of the area-integrated storm anomalies varies between the models, indicating that intermodel uncertainties in background ocean dynamics and biogeochemistry feed back onto synoptic anomalous fluxes. Our results highlight the

complexities in understanding how high-frequency activity contributes to the Southern Ocean climate on longer time scales. Considering the multifaceted changes to climate induced by anthropogenic emissions, it will be vital to understand how these seasonal imprints are controlled, which will help determine the future role of storms toward Southern Ocean heat and carbon uptake.

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Data availability statement. Code for the storm identification, storm-track postprocessing, composite creation, and analysis for figures in the manuscript can be found at <https://doi.org/10.5281/zenodo.14037201>. Due to the large (order of terabytes) amount of daily data involved in the analysis, full model fields and the regridded, storm-centered data are available upon request.

REFERENCES

- Adcroft, A., and Coauthors, 2019: The GFDL global ocean and sea ice model OM4.0: Model description and simulation features. *J. Adv. Model. Earth Syst.*, **11**, 3167–3211, <https://doi.org/10.1029/2019MS001726>.
- Banerjee, A., J. C. Fyfe, L. M. Polvani, D. Waugh, and K.-L. Chang, 2020: A pause in Southern Hemisphere circulation trends due to the Montreal protocol. *Nature*, **579**, 544–548, <https://doi.org/10.1038/s41586-020-2120-4>.
- Bjerknes, J., 1919: On the structure of moving cyclones. *Mon. Wea. Rev.*, **47**, 95–99, [https://doi.org/10.1175/1520-0493\(1919\)47<95:OTSOMC>2.0.CO;2](https://doi.org/10.1175/1520-0493(1919)47<95:OTSOMC>2.0.CO;2).
- Bushinsky, S. M., and Coauthors, 2019: Reassessing Southern Ocean air-sea CO₂ flux estimates with the addition of biogeochemical float observations. *Global Biogeochem. Cycles*, **33**, 1370–1388, <https://doi.org/10.1029/2019GB006176>.
- Carranza, M. M., M. C. Long, A. Di Luca, A. J. Fassbender, K. S. Johnson, Y. Takeshita, P. Mongwe, and K. E. Turner, 2024: Extratropical storms induce carbon outgassing over the Southern Ocean. *npj Climate Atmos. Sci.*, **7**, 106, <https://doi.org/10.1038/s41612-024-00657-7>.
- DeVries, T., 2014: The oceanic anthropogenic CO₂ sink: Storage, air-sea fluxes, and transports over the industrial era. *Global Biogeochem. Cycles*, **28**, 631–647, <https://doi.org/10.1002/2013GB004739>.
- Dunne, J. P., and Coauthors, 2020a: The GFDL Earth System Model version 4.1 (GFDL-ESM 4.1): Overall coupled model description and simulation characteristics. *J. Adv. Model. Earth Syst.*, **12**, e2019MS002015, <https://doi.org/10.1029/2019MS002015>.
- , and Coauthors, 2020b: Simple global ocean Biogeochemistry with Light, Iron, Nutrients and Gas version 2 (BLINGv2): Model description and simulation characteristics in GFDL's

- CM4.0. *J. Adv. Model. Earth Syst.*, **12**, e2019MS002008, <https://doi.org/10.1029/2019MS002008>.
- Eyring, V., S. Bony, G. A. Meehl, C. A. Senior, B. Stevens, R. J. Stouffer, and K. E. Taylor, 2016: Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6) experimental design and organization. *Geosci. Model Dev.*, **9**, 1937–1958, <https://doi.org/10.5194/gmd-9-1937-2016>.
- Fox-Kemper, B., and Coauthors, 2011: Parameterization of mixed layer eddies. III: Implementation and impact in global ocean climate simulations. *Ocean Modell.*, **39**, 61–78, <https://doi.org/10.1016/j.ocemod.2010.09.002>.
- , and Coauthors, 2021: Ocean, cryosphere and sea level change. *Climate Change 2021: The Physical Science Basis*, V. Masson-Delmotte et al., Eds., Cambridge University Press, 1211–1361, https://www.ipcc.ch/report/ar6/wg1/downloads/report/IPCC_AR6_WGI_Chapter09.pdf.
- Frenger, I., N. Gruber, R. Knutti, and M. Münnich, 2013: Imprint of Southern Ocean eddies on winds, clouds and rainfall. *Nat. Geosci.*, **6**, 608–612, <https://doi.org/10.1038/ngeo1863>.
- Frölicher, T. L., J. L. Sarmiento, D. J. Paynter, J. P. Dunne, J. P. Krasting, and M. Winton, 2015: Dominance of the Southern Ocean in anthropogenic carbon and heat uptake in CMIP5 models. *J. Climate*, **28**, 862–886, <https://doi.org/10.1175/JCLI-D-14-00117.1>.
- Gentile, E. S., M. Zhao, and K. Hodges, 2023: Poleward intensification of midlatitude extreme winds under warmer climate. *npj Climate Atmos. Sci.*, **6**, 219, <https://doi.org/10.1038/s41612-023-00540-x>.
- Gnanadesikan, A., M.-A. Pradal, and R. Abernathy, 2015: Isopycnal mixing by mesoscale eddies significantly impacts oceanic anthropogenic carbon uptake. *Geophys. Res. Lett.*, **42**, 4249–4255, <https://doi.org/10.1002/2015GL064100>.
- Gruber, N., P. Landschützer, and N. S. Lovenduski, 2019: The variable Southern Ocean carbon sink. *Annu. Rev. Mar. Sci.*, **11**, 159–186, <https://doi.org/10.1146/annurev-marine-121916-063407>.
- Hauck, J., and Coauthors, 2023: The Southern Ocean carbon cycle 1985–2018: Mean, seasonal cycle, trends, and storage. *Global Biogeochem. Cycles*, **37**, e2023GB007848, <https://doi.org/10.1029/2023GB007848>.
- Held, I. M., and Coauthors, 2019: Structure and performance of GFDL's CM4.0 climate model. *J. Adv. Model. Earth Syst.*, **11**, 3691–3727, <https://doi.org/10.1029/2019MS001829>.
- Hersbach, H., and Coauthors, 2020: The ERA5 global reanalysis. *Quart. J. Roy. Meteor. Soc.*, **146**, 1999–2049, <https://doi.org/10.1002/qj.3803>.
- Horowitz, L. W., and Coauthors, 2020: The GFDL global atmospheric chemistry-climate model AM4.1: Model description and simulation characteristics. *J. Adv. Model. Earth Syst.*, **12**, e2019MS002032, <https://doi.org/10.1029/2019MS002032>.
- Hoskins, B. J., and K. I. Hodges, 2002: New perspectives on the Northern Hemisphere winter storm tracks. *J. Atmos. Sci.*, **59**, 1041–1061, [https://doi.org/10.1175/1520-0469\(2002\)059<1041:NPOTNH>2.0.CO;2](https://doi.org/10.1175/1520-0469(2002)059<1041:NPOTNH>2.0.CO;2).
- , and —, 2005: A new perspective on Southern Hemisphere storm tracks. *J. Climate*, **18**, 4108–4129, <https://doi.org/10.1175/JCLI3570.1>.
- , and —, 2019: The annual cycle of Northern Hemisphere storm tracks. Part I: Seasons. *J. Climate*, **32**, 1743–1760, <https://doi.org/10.1175/JCLI-D-17-0870.1>.
- Johnson, K. S., and Coauthors, 2017: Biogeochemical sensor performance in the SOCCOM profiling float array. *J. Geophys. Res. Oceans*, **122**, 6416–6436, <https://doi.org/10.1002/2017JC012838>.
- Keppler, L., Y. A. Eddebbar, S. T. Gille, N. Guisewhite, M. R. Mazloff, V. Tamsitt, A. Verdy, and L. D. Talley, 2024: Effects of mesoscale eddies on Southern Ocean biogeochemistry. *AGU Adv.*, **5**, e2024AV001355, <https://doi.org/10.1029/2024AV001355>.
- Lenton, A., and Coauthors, 2013: Sea–air CO₂ fluxes in the Southern Ocean for the period 1990–2009. *Biogeosciences*, **10**, 4037–4054, <https://doi.org/10.5194/bg-10-4037-2013>.
- Lévy, M., P. J. Franks, and K. S. Smith, 2018: The role of submesoscale currents in structuring marine ecosystems. *Nat. Commun.*, **9**, 4758, <https://doi.org/10.1038/s41467-018-07059-3>.
- Li, Z., M. H. England, S. Groeskamp, I. Cerovečki, and Y. Luo, 2021: The origin and fate of subantarctic mode water in the Southern Ocean. *J. Phys. Oceanogr.*, **51**, 2951–2972, <https://doi.org/10.1175/JPO-D-20-0174.1>.
- Locarnini, R. A., and Coauthors, 2013: *Temperature*. Vol. 1, *World Ocean Atlas 2013*, NOAA Atlas NESDIS 73, 48 pp., <https://repository.library.noaa.gov/view/noaa/14847>.
- Marshall, J., and K. Speer, 2012: Closure of the meridional overturning circulation through Southern Ocean upwelling. *Nat. Geosci.*, **5**, 171–180, <https://doi.org/10.1038/ngeo1391>.
- Mazloff, M. R., P. Heimbach, and C. Wunsch, 2010: An eddy-permitting Southern Ocean state estimate. *J. Phys. Oceanogr.*, **40**, 880–899, <https://doi.org/10.1175/2009JPO4236.1>.
- Mongwe, N. P., M. Vichi, and P. M. S. Monteiro, 2018: The seasonal cycle of pCO₂ and CO₂ fluxes in the Southern Ocean: Diagnosing anomalies in CMIP5 Earth system models. *Biogeosciences*, **15**, 2851–2872, <https://doi.org/10.5194/bg-15-2851-2018>.
- Monteiro, P. M. S., L. Gregor, M. Lévy, S. Maenner, C. L. Sabine, and S. Swart, 2015: Intraseasonal variability linked to sampling alias in air–sea CO₂ fluxes in the Southern Ocean. *Geophys. Res. Lett.*, **42**, 8507–8514, <https://doi.org/10.1002/2015GL066009>.
- Neu, U., and Coauthors, 2013: IMILAST: A community effort to intercompare extratropical cyclone detection and tracking algorithms. *Bull. Amer. Meteor. Soc.*, **94**, 529–547, <https://doi.org/10.1175/BAMS-D-11-00154.1>.
- Nicholson, S.-A., D. B. Whitt, I. Fer, M. D. du Plessis, A. D. Lebéhot, S. Swart, A. J. Sutton, and P. M. Monteiro, 2022: Storms drive outgassing of CO₂ in the subpolar Southern Ocean. *Nat. Commun.*, **13**, 158, <https://doi.org/10.1038/s41467-021-27780-w>.
- Priestley, M. D. K., and J. L. Catto, 2022a: Improved representation of extratropical cyclone structure in HighResMIP models. *Geophys. Res. Lett.*, **49**, e2021GL096708, <https://doi.org/10.1029/2021GL096708>.
- , and —, 2022b: Future changes in the extratropical storm tracks and cyclone intensity, wind speed, and structure. *Wea. Climate Dyn.*, **3**, 337–360, <https://doi.org/10.5194/wcd-3-337-2022>.
- , D. Ackerley, J. L. Catto, K. I. Hodges, R. E. McDonald, and R. W. Lee, 2020: An overview of the extratropical storm tracks in CMIP6 historical simulations. *J. Climate*, **33**, 6315–6343, <https://doi.org/10.1175/JCLI-D-19-0928.1>.
- , —, —, and —, 2023: Drivers of biases in the CMIP6 extratropical storm tracks. Part II: Southern Hemisphere. *J. Climate*, **36**, 1469–1486, <https://doi.org/10.1175/JCLI-D-20-0977.1>.
- Reichl, B. G., and R. Hallberg, 2018: A simplified energetics based planetary boundary layer (ePBL) approach for ocean climate simulations. *Ocean Modell.*, **132**, 112–129, <https://doi.org/10.1016/j.ocemod.2018.10.004>.

- Russell, J. L., K. W. Dixon, A. Gnanadesikan, R. J. Stouffer, and J. R. Toggweiler, 2006: The Southern Hemisphere westerlies in a warming world: Propping open the door to the deep ocean. *J. Climate*, **19**, 6382–6390, <https://doi.org/10.1175/JCLI3984.1>.
- Shaw, T. A., and Coauthors, 2016: Storm track processes and the opposing influences of climate change. *Nat. Geosci.*, **9**, 656–664, <https://doi.org/10.1038/ngeo2783>.
- Shevliakova, E., and Coauthors, 2024: The land component LM4.1 of the GFDL Earth System Model ESM4.1: Model description and characteristics of land surface climate and carbon cycling in the historical simulation. *J. Adv. Model. Earth Syst.*, **16**, e2023MS003922, <https://doi.org/10.1029/2023MS003922>.
- Soci, C., and Coauthors, 2024: The ERA5 global reanalysis from 1940 to 2022. *Quart. J. Roy. Meteor. Soc.*, **150**, 4014–4048, <https://doi.org/10.1002/qj.4803>.
- Son, S.-W., N. F. Tandon, L. M. Polvani, and D. W. Waugh, 2009: Ozone hole and Southern Hemisphere climate change. *Geophys. Res. Lett.*, **36**, L15705, <https://doi.org/10.1029/2009GL038671>.
- Stern, A. A., A. Adcroft, O. Sergienko, and G. Marques, 2017: Modeling tabular icebergs submerged in the ocean. *J. Adv. Model. Earth Syst.*, **9**, 1948–1972, <https://doi.org/10.1002/2017MS001002>.
- Stock, C. A., and Coauthors, 2020: Ocean biogeochemistry in GFDL's Earth System Model 4.1 and its response to increasing atmospheric CO₂. *J. Adv. Model. Earth Syst.*, **12**, e2019MS002043, <https://doi.org/10.1029/2019MS002043>.
- Terhaar, J., N. Goris, J. D. Müller, T. DeVries, N. Gruber, J. Hauck, F. F. Perez, and R. Séférian, 2024: Assessment of global ocean biogeochemistry models for ocean carbon sink estimates in RECCAP2 and recommendations for future studies. *J. Adv. Model. Earth Syst.*, **16**, e2023MS003840, <https://doi.org/10.1029/2023MS003840>.
- Toggweiler, J. R., and B. Samuels, 1993: New radiocarbon constraints on the upwelling of abyssal water to the ocean's surface. *The Global Carbon Cycle*, M. Heimann, Ed., Springer, 333–366.
- Toolsee, T., S.-A. Nicholson, and P. M. S. Monteiro, 2024: Storm-driven pCO₂ feedback weakens the response of air-sea CO₂ fluxes in the sub-Antarctic Southern Ocean. *Geophys. Res. Lett.*, **51**, e2023GL107804, <https://doi.org/10.1029/2023GL107804>.
- Ullrich, P. A., C. M. Zarzycki, E. E. McClenny, M. C. Pinheiro, A. M. Stansfield, and K. A. Reed, 2021: TempestExtremes v2.1: A community framework for feature detection, tracking, and analysis in large datasets. *Geosci. Model Dev.*, **14**, 5023–5048, <https://doi.org/10.5194/gmd-14-5023-2021>.
- Verdy, A., and M. R. Mazloff, 2017: A data assimilating model for estimating Southern Ocean biogeochemistry. *J. Geophys. Res. Oceans*, **122**, 6968–6988, <https://doi.org/10.1002/2016JC012650>.
- Whitt, D. B., S. A. Nicholson, and M. M. Carranza, 2019: Global impacts of subseasonal (<60 day) wind variability on ocean surface stress, buoyancy flux, and mixed layer depth. *J. Geophys. Res. Oceans*, **124**, 8798–8831, <https://doi.org/10.1029/2019JC015166>.
- Williams, R. G., P. Goodwin, V. M. Roussenov, and L. Bopp, 2016: A framework to understand the transient climate response to emissions. *Environ. Res. Lett.*, **11**, 015003, <https://doi.org/10.1088/1748-9326/11/1/015003>.
- , P. Ceppi, V. Roussenov, A. Katavouta, and A. J. S. Meijers, 2023: The role of the Southern Ocean in the global climate response to carbon emissions. *Philos. Trans. Roy. Soc.*, **A381**, 20220062, <https://doi.org/10.1098/rsta.2022.0062>.
- , A. J. S. Meijers, V. M. Roussenov, A. Katavouta, P. Ceppi, J. P. Rosser, and P. Salvi, 2024: Asymmetries in the Southern Ocean contribution to global heat and carbon uptake. *Nat. Climate Change*, **14**, 823–831, <https://doi.org/10.1038/s41558-024-02066-3>.
- Woollings, T., B. Hoskins, M. Blackburn, D. Hassell, and K. Hodges, 2010: Storm track sensitivity to sea surface temperature resolution in a regional atmosphere model. *Climate Dyn.*, **35**, 341–353, <https://doi.org/10.1007/s00382-009-0554-3>.
- , J. M. Gregory, J. G. Pinto, M. Reyers, and D. J. Brayshaw, 2012: Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling. *Nat. Geosci.*, **5**, 313–317, <https://doi.org/10.1038/ngeo1438>.
- Zhao, M., and Coauthors, 2018a: The GFDL global atmosphere and land model AM4.0/LM4.0: 1. Simulation characteristics with prescribed SSTs. *J. Adv. Model. Earth Syst.*, **10**, 691–734, <https://doi.org/10.1002/2017MS001208>.
- , and Coauthors, 2018b: The GFDL global atmosphere and land model AM4.0/LM4.0: 2. Model description, sensitivity studies, and tuning strategies. *J. Adv. Model. Earth Syst.*, **10**, 735–769, <https://doi.org/10.1002/2017MS001209>.
- Zweng, M. M., and Coauthors, 2013: *Salinity*. Vol. 2, *World Ocean Atlas 2013*, NOAA Atlas NESDIS 74, 47 pp., https://www.ncei.noaa.gov/sites/default/files/2020-04/woa13_vol2.pdf.